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Abstract

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The flux of primary cosmic-ray α-particles was measured in nuclear photographic emulsions exposed on a high altitude balloon flight in Texas, in April 1965. The flux value derived was 110 ± 8 particles/m^2 sec. ster, substantially in excess of that expected on the basis of data obtained in 1954-6, at the time of the previous minimum in solar activity. A re-examination of published records of older flights shows that the geomagnetic cut-off values assumed were in error. Discussions of solar modulation effects in the high energy region will require modification.

I. Introduction

In recent years, the general features of the cosmic radiation have been delineated and the effects of solar modulation have been observed. Despite the steady progression of our knowledge, there are many points on which we would wish to have much more detailed information, and the physics of the modulating mechanism is by no means clearly understood. The 1965 minimum in the cycle of solar activity presented an opportunity to study the galactic radiation in a relatively undisturbed condition. Accordingly, we exposed nuclear photographic emulsions to the primary radiation via a balloon flight from Palestine, Texas, in April 1965. The α-particle flux derived was sufficiently in excess of that expected on the basis of the 1954-6 values, that a more detailed analysis was prompted.

Careful examination of the contours of geomagnetic cut-off provides the explanation. A re-examination of the data published by many groups over the years, demonstrates clearly that the cut-off values often assumed are incorrect; correspondingly, the analyses of the effects of modulation in the high energy region during the solar cycle must be altered.

II. Experimental Procedures and Results

In the flight on 24th April, 1965, the balloon maintained the emulsions at an average pressure altitude of 2.7 mb for 9 hr 26 min, with little variation, this time being calculated from the instant of emulsion rotation after ascent. Two stacks of pellicles and a set of glass-backed emulsions were included in the flight package. The data reported here were obtained in an examination of a few of the pellicles; the remainder of the pellicles are being examined for the tracks of particles with $Z \geq 3$, while the glass-backed plates will be used for multiple scattering measurements towards an energy spectrum in the region from cut-off up to about 10 Gev/nucleon.

An appendix to this paper contains details of the emulsion measurements, while in this section we list only the results.

The flux value quoted is based upon the observation of 242 α-particles which crossed the scan line within a well-defined solid angle. Emulsion thickness, a quantity which enters into the calculation of the geometrical factor, was calibrated. Tracks for analysis were obtained by systematic scanning, but, as always with this type of experiment, repeated scanning was required in order to estimate the scanning efficiency, which was found to be 88 ± 3%.

To extrapolate from the flux of α-particles observed crossing the scan line, to the flux incident upon the top of the atmosphere requires corrections for (i) loss of α-particles through interaction in the atmosphere above the emulsions, (ii) loss of α-particles through interaction in the emulsions but above the scan line and (iii) production of α-particles as secondaries arising in the fragmentation of heavier primary particles. These corrections come to (i) +6.7%, (ii) +6.0% and (iii) -1%. The uncertainties in these values are negligible, and the appendix contains a more extended discussion on these points.

The flux of primary α-particles, at the top of the atmosphere, is finally calculated to be

$$J_\alpha = 110 \pm 8 \text{ particles/m}^2\text{. sec. ster.}$$

III. Discussion

On the basis of data from several balloon flights in the Texas region and one at a closely similar geomagnetic latitude in northern Italy, Waddington[1] has estimated the flux of primary α-particles to have been 88 $\pm$ 2 particles/m^2. sec. ster. at the time of minimum solar activity. Webber[2] [3], has made use of more recent results and has correlated them with neutron monitor rates to arrive at a value of 94 $\pm$ 4 particles/m^2. sec. ster. These flux values have been taken to refer to the integral flux of α-particles having magnetic rigidities $R \geqslant 4.5$ GV (although this figure has sometimes been quoted as 4.6 GV).

The flux value which we derive from the current experiment, 110 $\pm$ 8 particles/m^2. sec. ster, is 16 $\pm$ 9 higher than Webber's estimate (above) and we feel that this difference is physically significant.

A detailed examination of the variation of geomagnetic cut-off in the Texas-New Mexico flight region provides a consistent explanation of most of the experimental results. Figure 1 shows contours of equal cut-off rigidity, obtained from the calculations of Quenby and Wenk[4]. These authors used an approximation procedure which has been shown, by detailed particle trajectory tracings, to be reliable in this region. Also marked in the figure are the balloon launch sites most frequently used. As can be seen, these are by no means at the same cut-off. With an integral energy spectrum of $J(\geq W) \propto W^{-1.5}$, a change in cut-off from 4.5 GV to 5.0 GV will produce a decrease of 16% in the α-particle flux. (W = total energy/nucleon).

In Table 1 and Figure 2, we have summarised those data which we consider pertinent to the present discussion. By reference to Fig. 1 and published works, we have been able to assign effective cut-off values corresponding to the mid-point between launch and recovery locations for each flight. We have excluded from our analysis several flux values which Webber[3] and Freier and Waddington[5] did include. These values were obtained from flights at northern latitudes and the intrinsic resolution of those experiments was insufficient to distinguish between 1.5 Gev/nucleon and 1.73 Gev/nucleon kinetic energies, corresponding to 4.5 GV and 5.0 GV respectively. We retain only those flights which were conducted in a region of high cut-off. Most of these appear to have been at an effective cut-off very close to 5.0 GV. Apart from our own flight, there was none other at 4.5 GV, but there were three at 4.7 GV and 4.8 GV.

These data are displayed in Figure 2, where the integral flux values are plotted against the rate of the Mt. Washington neutron monitor. With only one flux value having been observed for 4.5 GV cut-off, it is clear that no very reliable regression line can be constructed. The three points at 4.7 GV and 4.8 GV we have scaled to flux values expected for a cut-off of 4.5 GV, assuming an integral spectrum in total energy having the form $W^{-1.5}$. In their original positions, these three points influence very strongly the regression line fitted by Webber. Scaling to 4.5 GV at least gives some indication as to where the 4.5 GV regression line might lie; scaling these same three points to 5.0 GV brings them into excellent agreement with the regression line through the points which definitely correspond to 5.0 GV. For comparison, we have also shown the regression line which Webber(3) has calculated. This is markedly different from those which we have deduced here and which we feel form a more reliable basis for further discussion.

For a comparison of experimental results with the many models which have been constructed to describe the solar modulation process, differential energy spectra are needed, and this has been best accomplished in the region appreciably below 1 Gev/nucleon. Differential energy spectra have been obtained in this laboratory between about 1.5 Gev/nucleon and about 10 Gev/nucleon, by the use of glass-backed emulsions and multiple scattering measurements, but the energy resolution is such that while these experiments serve to establish the slope of the spectrum, the statistical uncertainties make it impossible to deduce a reliable value for the differential flux in the region just above cut-off. This can, though, be deduced from independent observations of the integral fluxes at 4.5 GV and 5.0 GV. In principle, the separation of the regression lines in Fig. 2, through the 4.5 GV and 5.0 GV points, can be used to calculate the flux in that rigidity (or energy) interval. Accumulation of a far greater quantity of data through the present solar cycle would provide a reasonable basis for such a calculation, which the present meager data do not justify.

It would seem worthwhile to conduct flights not only from Palestine but also from places with a slightly higher cut-off, such as San Angelo and Alamogordo, so that the modulation can be examined in this narrow rigidity interval. In such flights, as well as from a re-examination of the records of older flights, it should be possible to observe the change in α-particle flux as the balloon drifts across the geomagnetic contours.

Acknowledgements:

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Appendix A: Further details of experimental techniques and corrections.

The two stacks of emulsions each held 125 pellicles, of size 20 cm (horizontal) by 5 cm (vertical) by 0.593 mm original thickness. Scanning for α-particles was conducted along a line 1.2 cm below the top of the stack, and was designed to record tracks which were, by inspection, of the correct grain density (around four times that for fast protons), and also satisfied strict geometrical criteria. From these scan records, one of us has examined every track, and identified the α-particles, which were further restricted to those within 30° of the projected zenith and had projected lengths of at least 5 mm per emulsion.

Identification of tracks as having been produced by fast α-particles was mostly by inspection, using a Koristka R4 microscope. As a check, 55 tracks were subjected to multiple scattering measurements and the clear separation between singly and doubly charged particles was observed. We consider that the possible presence of singly charged particles amongst the claimed α-particles is negligible.

In 10 scans, each 6 cm long, 242 α-particle tracks were found, satisfying the criteria listed above and also identified as primaries by being traced back to their entry points at the top edge of the stack.

In the extrapolation back from the scan line, the following corrections have been included:

(a) loss of α-particles in the 1.2 cm of emulsion above the scan line. Using 20 cm as the value of the α-particle mean free path in emulsion and averaging over the acceptable cone of zenith angles, the correction to be applied is +6.7%.

(b) loss of α-particles in the 2.9 gm/cm^2 of atmosphere plus packing above the top of the emulsions. Here, a mean free path of 55 gm/cm^2 has been used[5], leading to a correction of +6.0%.

(c) production of fast α-particles arising in the fragmentation of heavier particles: -1%, using $P_{HP,\alpha} \sim 1$, $J_{HP}/J_{\alpha} \sim 0.1$ and $\lambda_{HP} \sim 30$ gm/cm^2.

(d) scanning efficiency: 40% of the area, in which 107 α-particles had originally been found, was re-scanned. We have used the method of analysis described by Lim et al[6] and Waddington[7], and have also taken into account the slightly different efficiencies of the two microscopists. The weighted mean efficiency, which we use in correcting the flux value, is (88 ± 3)%.

At the scan line, the 242 α-particles correspond to a flux of 86.4 particles/m^2. sec. ster. Extrapolation of this to the top of the atmosphere raises this to 96.7 particles/m^2. sec. ster. Finally, including the scanning efficiency, we arrive at the value

$$J_\alpha = 110 \pm 8 \text{ particles/m}^2\text{. sec. ster.}$$

The standard deviation quoted is the statistical error based mainly upon the number of particles in our sample and the uncertainty in the scanning efficiency. Uncertainties in the parameters used in the extrapolation corrections are negligible.

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Table 1.

Authors & Reference	Flight Date	Launch Site	Average Cut-off R(GV)*	Flux α/m^2 sec.sr	Mt. Wash. neutron rate
McDonald & Webber[2]	22.1.55	San Angelo	5.0	89 ± 8	2420
.. ..	4.2.59	Brownwood	4.7	72 ± 4	2078
.. ..	11.2.59	..	4.8	75 ± 4	2034
Waddington[8]	14.9.54	N. Italy	5.0	88 ± 13	2470
Fowler, Freier, Ney[9]	6.2.56	San Angelo	5.1	97 ± 8**	2430
Engler, Kaplon, Klarmann[10]	6.2.56	San Angelo	5.1	90 ± 8**	2430
Freier, Ney, Waddington[11]	19.10.57	San Angelo	5.0	68 ± 4	2048
Guss[12]	8.2.59	Brownwood	4.7	75 ± 4	2021
Neelakantan & Biswas[13]	26.3.62	..	5.0	78 ± 9	2220
Foster & Schrautemeier[14]	14.5.62	Alamogordo	5.0	80 ± 7	2225
present experiment	23.4.65	Palestine	4.5	110 ± 8	2459

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Notes*: Cut-off computed for midpoint between launch and recovery locations.

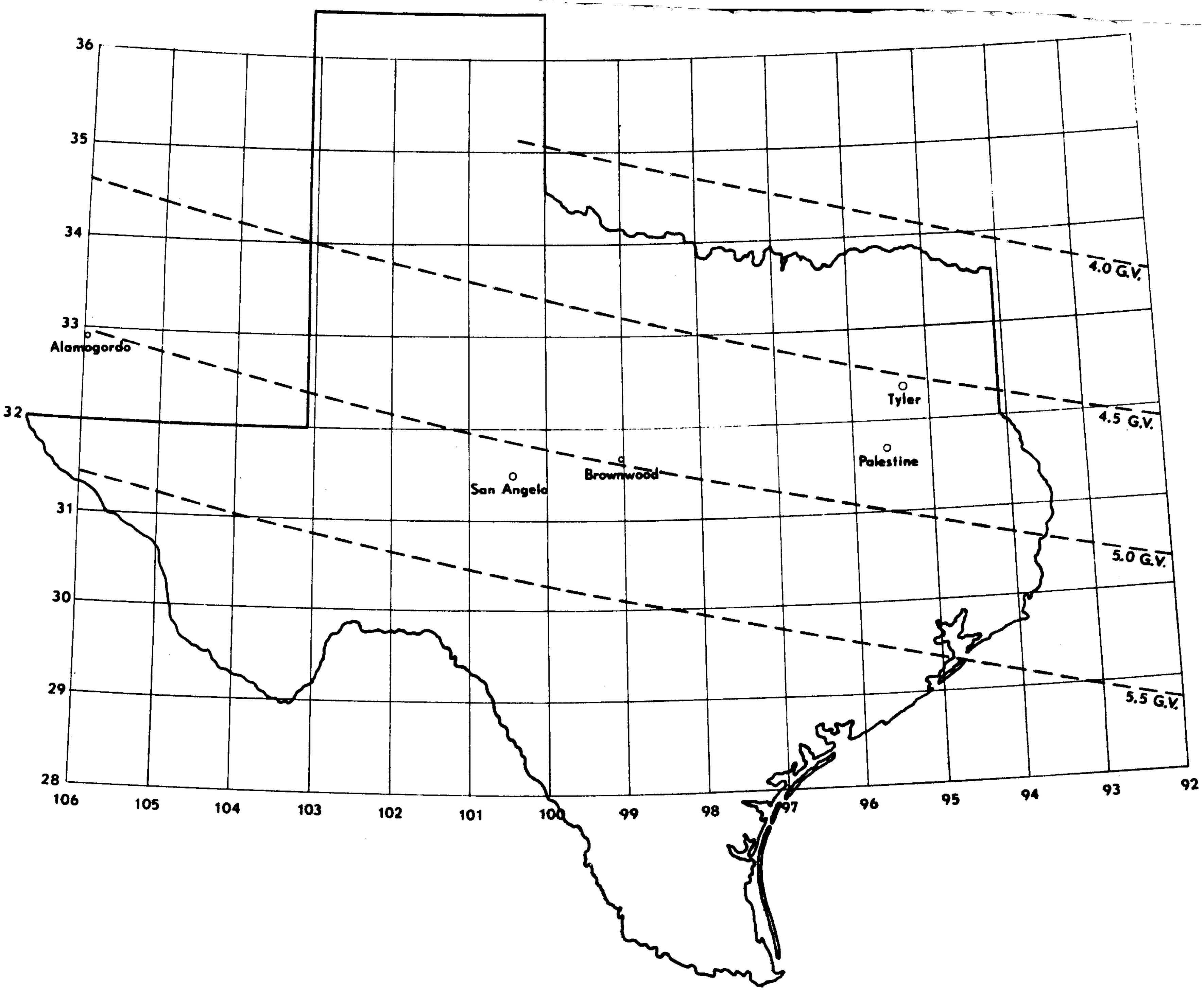
**: Scaled to 5.0 GV cut-off in Fig. 2.

Captions to Figures:

Fig. 1.: Contours of equal cut-off rigidity, at 0.5 GV intervals, with balloon launch sites shown.

Fig. 2.: Variation of α-particle flux as shown by correlation with Mt. Washington neutron monitor rates. Points ⊙ are observed fluxes: scaling to cut-off of 4.5 GV leads to the points ✗ while scaling to 5.0 GV leads to the points ● . Two points which were originally at 5.1 GV have been scaled to 5.0 GV and are shown thus: ▢ .

Regression lines through the 4.5 GV and 5.0 GV points are shown as full lines. Webber's 4.5 GV line is shown for comparison, as a dashed line.



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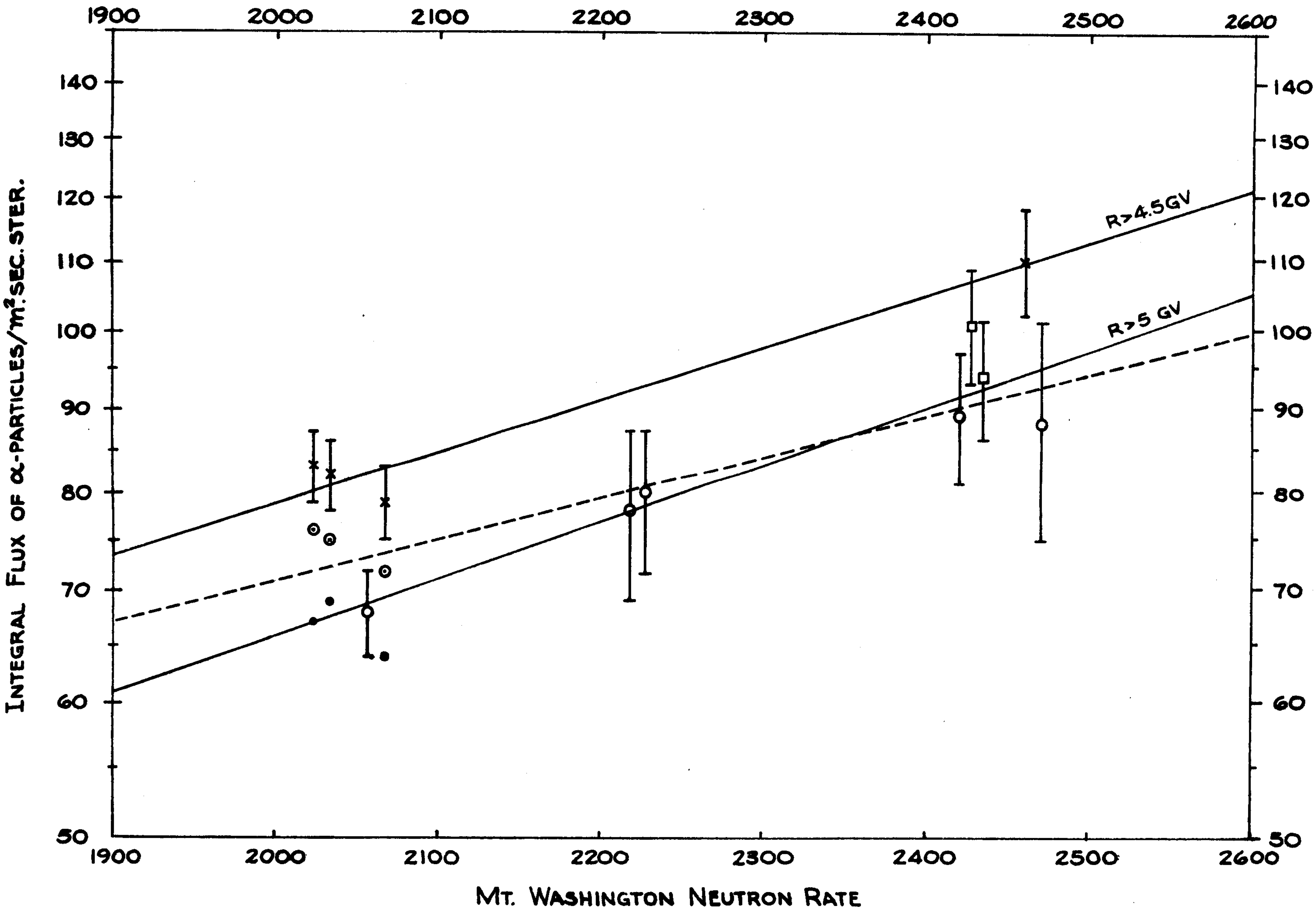
Alamogordo
Tyler
Palestine
Brownwood
San Angelo



R>4.5GV
R>5 GV
INTEGRAL FLUX OF α-PARTICLES/m².SEC.STER.
MT. WASHINGTON NEUTRON RATE